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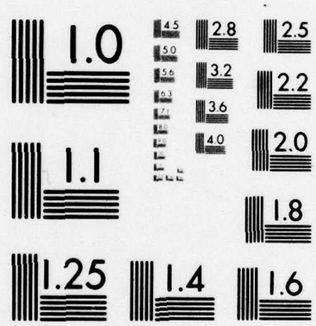

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RESULTS OF A COMPARISON BETWEEN THE LINDAU FOIL CLOUD EXPERIMENT AND THE INFLATABLE FALLING SPHERE EXPERIMENT

July 1979

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Under Contract DAERO-75-G-076 new
CONTRACT MONITOR: R.O. Olsen

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US Army Electronics Research and Development Command
ATMOSPHERIC SCIENCES LABORATORY
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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ASL-CR-79-076-1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) RESULTS OF A COMPARISON BETWEEN THE LINDAU FOIL CLOUD EXPERIMENT AND THE INFLATABLE FALLING SPHERE EXPERIMENT		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) G. Rose and H. U. Widdel		8. CONTRACT OR GRANT NUMBER(s) DAERO-75-G-076 new
9. PERFORMING ORGANIZATION NAME AND ADDRESS Max-Planck-Institute fur Aeronomie D-3411 Katlenburg-Lindau 3, Federal Republic of Germany		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS DA Task No. 1L162111AH71
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Electronics Research and Development Command Adelphi, MD 20783		12. REPORT DATE July 1979
		13. NUMBER OF PAGES 31
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Atmospheric Sciences Laboratory White Sands Missile Range, NM 88002		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

(12) 30p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Contract Monitor: R. O. Olsen

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Lindau foil cloud
Inflatable falling sphere
Density and temperature measurements

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Between 10 and 24 April 1974, a series of rocket flights was launched at White Sands Missile Range as part of a cooperative project between the Arbeitsgruppe D-Schicht-Aeronomie of the Max-Planck-Institute fur Aeronomie and the US Army Atmospheric Sciences Laboratory. Primarily, the purpose was to compare wind sensing techniques in the height range between 95 and 80 km. In addition, the foil chaff clouds are capable of providing neutral air density over the height interval from 85 to 92 km. The inflatable falling sphere experiment is capable

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20. ABSTRACT (cont)

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of deriving density, temperature, and wind data between 35 and 90 km, with less accuracy above 85 km. The foil chaff cloud is primarily intended to measure winds and wind shears between 95 and 75 km with good height resolution due to its low fall velocity. The foil chaff can also be used to determine density, pressure and--within certain limits--air temperatures for smaller height interval from 95 to about 85 km. However, some assumptions have been made in deriving the additional thermodynamic data.

CONTENTS

INTRODUCTION

Between 10 and 24 April 1974, a series of rocket flights was launched at White Sands Missile Range as part of a cooperative project between the Arbeitsgruppe D-Schicht-Aeronomie of the Max-Planck-Institute fur Aeronomie and the Atmospheric Sciences Laboratory. Primarily, the purpose was to compare wind sensing techniques in the height range between 95 and 80 km. In addition, the foil chaff clouds are capable of providing neutral air density over the height interval from 85 to 92 km (figure 1). The inflatable falling sphere experiment is capable of deriving density, temperature, and wind data between 35 and 90 km, with less accuracy above 85 km. The foil chaff cloud is primarily intended to measure winds and wind shears between 95 and 75 km with good height resolution due to its low fall velocity. The foil chaff can also be used to determine density, pressure and--within certain limits--air temperatures for smaller height intervals from 95 to about 85 km. However, some assumptions have been made in deriving the additional thermodynamic data.

The foil chaff cloud consists of ultralight, aluminized, band-like reflectors cut at a length resonant with the radar frequency. Wind sensors of this type have been used frequently in the past.[1,2] The foil chaff used in this series differs from its predecessors in that special means were taken to ensure that the dipole elements were completely separated from each other, and steps were taken to reduce the influence of the horizontal and vertical component of the rocket's velocity on the spread of the sensor cloud by ejecting it in a backward direction near the rocket's apogee (figure 2). By this method, the horizontal component of the rocket velocity is compensated for.

The foil cloud experiment used at White Sands was patterned after the type which had been used in the past at Arenosillo, the Spanish National Rocket Range. This payload contained a minimum of 50,000 to 60,000 dipole elements from which the cloud is formed, instead of a few hundred or a few thousand which are sufficient for high power radars. A total of four Sidewinder boosted ARCAS vehicles, two Super Loki inflatable falling spheres, and two Loki Datasonde systems were flown before and after each pair of foil chaff cloud launches. The series were launched as close to local noon as the schedule allowed, to permit some comparison with the results obtained in a series of launches performed at Arenosillo in Southern Spain.

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[1]L. G. Smith, 1960, "The measurement of winds between 100,000 and 300,000 ft by use of chaff rockets," J Meteorol, 17:296-310

[2]J. C. Manning and L. W. Chamberlain, 1968, "Measurements of winds and temperatures at altitudes up to 65 kilometers in the Southern Hemisphere," NASA Technical Note TN D-4429, National Aeronautics and Space Administration, Washington, DC

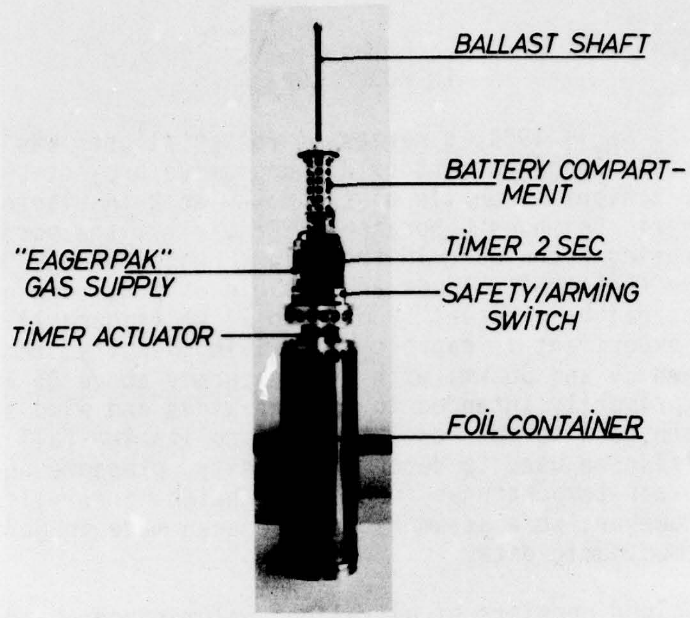

Figure 1. Foil cloud payload used on ARCAS vehicles at WSMR. Lightweight design: foil container is made from 0.2-mm thick aluminum sheet material, reinforced with profile stringers glued to the outside with epoxy resin. Holes were drilled into structure wherever possible to lighten structure. Weight 1.9 kg.

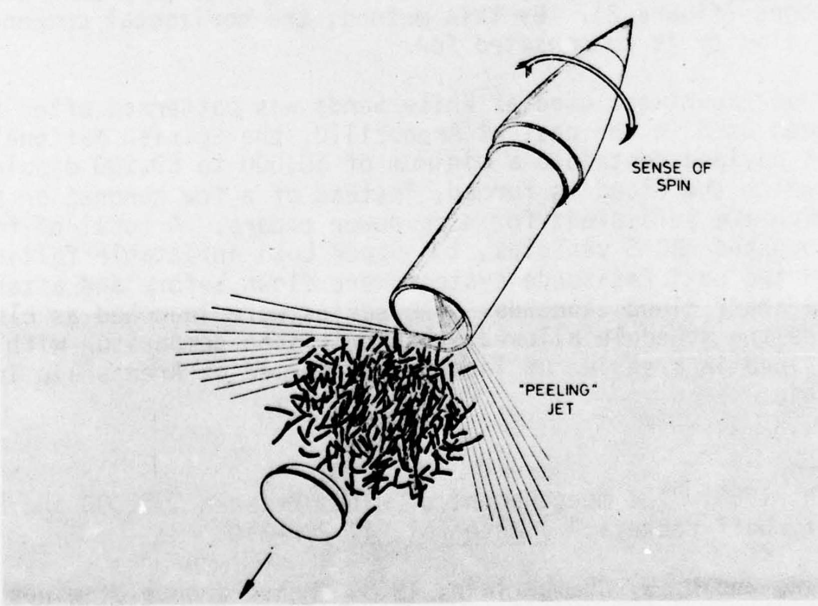

Figure 2. Method of foil cloud generation: the payload is separated from the rocket. After 2 s, gas vessels are opened. The foils are ejected from the canister; but two jets, oriented backwards at about 30 deg against the sense of spin, "peel off" the bunch of foils and help to separate them, creating at the same time a denser "core" which helps the radar operator to treat the target as a "point" target by reducing the receiver sensitivity. Backward ejection of foils compensates (at least partly) vertical and horizontal speed component of the rocket.

For a number of technical reasons, only two of the Sidewinder boosted ARCAS experiments yielded results, and there was a failure in acquiring data from the falling-sphere experiments. The foil cloud from the first boosted ARCAS sounding was not acquired by the assigned radar; another radar acquired the chaff cloud and followed the target for about 7 minutes but did not record tracking data. On the second flight, the drag separation between the Sidewinder booster and the boosted ARCAS was delayed by about 1 second, resulting in a reduced apogee. Because of the low apogee, the cloud was ejected at a low altitude, making it unsuitable for the derivation of the density and temperature values.

Based on the low altitude achieved by the second vehicle, the payload weight on the third vehicle was reduced. As a result, the cloud from the third launch was ejected at 105 km, a higher altitude than required. The foil chaff cloud on the upleg portion of the trajectory ascended for 52 seconds to an apogee of 120 km. From this altitude the cloud had to descend to a height of 95 km, the altitude at which the chaff was supposed to be deployed. This unexpected event not only caused a very unusual dispersion of the foil elements but also subjected the cloud to decelerations which are not experienced under usual conditions. For this flight series, no comparison data were available from the falling spheres above 70 km. On the fourth and last boosted ARCAS flight, the second stage ARCAS did not ignite, resulting in a low apogee. Because of this failure, an alternate solution was decided upon--to launch a Super Loki to deploy a small charge of foils. The foils were deployed at a height of 85 km, an altitude lower than expected; but this flight proved that a better quality of tracking could be achieved with a smaller number of foils and the precision radars available at White Sands Missile Range.

Nevertheless, these tests were quite helpful and permitted tests of the foil chaff cloud theory and the validity of the approximations used in the evaluation.

DENSITY AND TEMPERATURE IN THE UPPER ATMOSPHERE BY MEANS OF FREE FALLING

The descent velocity of a body released in the atmosphere can be used to determine the atmosphere's density and temperature provided that the aerodynamic flow around the body is known. The movement of the body is described by the equation

$$m\dot{v} = -mg - C_D A \frac{\rho}{2} v^2 , \qquad (1)$$

where m denotes the mass of the body, v the velocity, $\dot{v}$ the acceleration, g the gravitational acceleration, ρ the ambient density, A the cross section area, and C_D the drag coefficient which is a function of the

aerodynamical flow regime. Atmospheric density can be solved by using an equation where the foil characteristics are known and foil velocities and accelerations are derived from the radar track of the foil cloud.

When the density variation with height is known and the temperature has been assumed from a reference atmosphere, the height profile for temperature can be calculated by integrating with the hydrostatic equation:

$$T = \frac{m}{\rho k} \int_{z}^{z_o} \rho g dz + \frac{\rho_o}{\rho} T_o , \qquad (2)$$

where z denotes the height and k the Boltzmann constant; ρ_o, T_o are the relevant data for density and temperature at the reference height z_o; m is the mass of an air molecule.

The Meteorological Rocket Network utilizes a lightweight, inflatable mylar sphere as a wind and density sensor. The sphere is inflated by the release of isopentane. Ejection from the rocket takes place at a height up to 130 km. The sphere is completely metalized, which permits track of the target from the ground with a precision radar. To determine air density, the drag coefficient C_D of the sphere must be known. The drag coefficient C_D is a function of the Reynolds number

$$R_e = v \cdot \rho \cdot \frac{L}{\eta} ,$$

the Mach number v/u, and the ratio between the free path length of the molecules and the diameter of the sphere (the Knudsen number λ/L, which can be expressed by a combination of Mach number and Reynolds number). This function becomes important for the upper portion of the sphere's trajectory. Therefore:

$$C_D = C_D (R_e, M, \lambda/L). \qquad (3)$$

Quite extensive series of measurements of the drag coefficient for wide ranges of Mach and Reynolds numbers had to be made to make this principle for density and temperature measurement practical. Some details of these investigations are summarized in NASA Report Sp-219.[3]

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[3]NASA Report Sp-219, 1969, "Status of passive inflatable falling sphere technology for atmospheric sensing to 100 km," Symposium at Langley Research Center, Hampton, VA, 23-24 September 1969

For physical and technological reasons, the weight-to-area-ratio for spheres (and other types of sensors) cannot be made small enough to enable the descent speed to be subsonic at all heights to obtain enough data points to eliminate tracking errors of the radar and to remain in regimes of airflow which are simple to handle. This constraint in the weight-to-area-ratio results in the spheres obtaining supersonic velocities when deployed at the greater heights and going through a complicated deceleration phase when they reach lower heights and higher ambient densities. This effect and possibly other effects render it difficult to gain fairly accurate measurements of wind, density, and temperature in heights above 85 to 90 km. Due to the extremely low weight-to-area-ratio of the foil cloud sensor developed in Lindau,[4,5] the descent velocity of the cloud remains subsonic when ejected at heights around 95 to 98 km and yields more accurate data for winds and wind shears than the falling sphere method for the height interval of 95 to 85 km. The foils are 2.5μm thick, 9 mm wide and 50 mm long. (They were cut to S-band radar frequencies.) An arrangement of two jets of compressed nitrogen is used for proper separation of the foils and produces a spherical cloud with an increased foil density towards the center of the cloud.

With this technique, the radar operator can maintain a point target for a longer time period than usual by adjusting the radar sensitivity. Typical descent speeds for the foil cloud are 80 to 90 m/s at a height of 95 km. The speed decreases to 8 to 10 m/s at a height of 75 km which is in the same order of magnitude of the vertical gusts present in several upper atmosphere regions. These gusts very often cause dispersion of the foil cloud, making reasonable tracking impossible, with the result that data from lower heights are seldom utilized. Therefore, it is necessary to use two kinds of chaff elements, and each element is matched for a particular height region, for example, 95 to 83 km and 85 to 68 km to reliably sense the full height interval between 95 and 68 km.

While chaff clouds are generally accepted as a technique to measure winds, their usefulness for density and temperature measurements had been questioned in the past.[6] Whether the lightweight chaff could possibly be used to derive density and temperature requires experimental data because the accuracy of tracking the chaff is questionable. In February 1970, a series of experiments was performed for several days and nights. Chaff payloads were

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[4]A. Azcarraga and L. Sanchez, 1970, "On the structure of mesospheric winds," Space Research, X:174-179, North Holland publishing Company, Amsterdam

[5]W. Dieminger, G. Rose, and H. U. Widdel, 1974, Windbeobachtungen in der Mesosphare and Unteren Ionosphare. Naturwissenchaften, 61:225-231

[6]R. Rapp, 1969, "The accuracy of winds derived by the radar tracking of chaff at high altitudes," J Meteorol, 17:507-514

launched during 4 consecutive days, one every 4 hours. An examination of the descent velocities showed a consistent pattern of regular variations with time[7] which encouraged endeavors to convert the fall rates into density values.

Figure 3 shows the variation of the measured and descent velocity. One sees the characteristic increase of the descent speed around midnight, which corresponds to a decrease of air density at the relevant height about this time.

The first attempt at deriving density was confined to simply calibrating the measurements against the CIRA reference atmosphere, as is shown in figure 4, where the exponential decrease of the descent velocity with decreasing height mirrors the exponential decrease of the air density with height. The data collected at 2000 hours showed the least scatter, which indicated that turbulent vertical movements present over the day are much less intense at this time.

These and other measurements of fall rates of the chaff cloud provided data indicating that the deceleration of the foil elements as they descended was in the order of 0.1 g at a height of 95 km but decreased rapidly with decreasing height provided that the cloud was created above 95 km where a quasi-equilibrium descent velocity was achieved. The term $m\dot{v}$ in equation (1) can therefore be neglected below this altitude. In this case, the equation of the motion (1) simplifies to

$$mg = \frac{1}{2} C_D \cdot \rho A \cdot v^2 \ . \tag{4}$$

For a first approximation of the derivation of fall rates into densities, the drag coefficient can be determined by comparing average fall rates with CIRA density data for the required heights.

If C_D were constant, v^2 would be proportional to $1/\rho$ because the gravity forces represented on the left side of equation (4) can be assumed to be nearly independent of height; however, v^2 is not proportional to $1/\rho$. Therefore, ρ and v are first approximations of exponential functions of height and have been found empirically to be of the form $v = \text{const}\ \rho^{-0.76}$, between the altitude of 83 and 95 km.

With the determination of the proportionality constant and that of the exponent, the problem of deriving the fall rates can be calculated. The relation between air density and equilibrium descent velocity v is then determined empirically and one parameter can be adequately approximated by knowing the other parameter.

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[7]G. Rose and H. U. Widdel, 1972, "On the possibility of simultaneous measurement of wind speed, wind direction, air density and air temperatures at heights which correspond to the upper D-region (mx. 95 km) with chaff cloud sensors," Planet Space Sci, 20:877-889

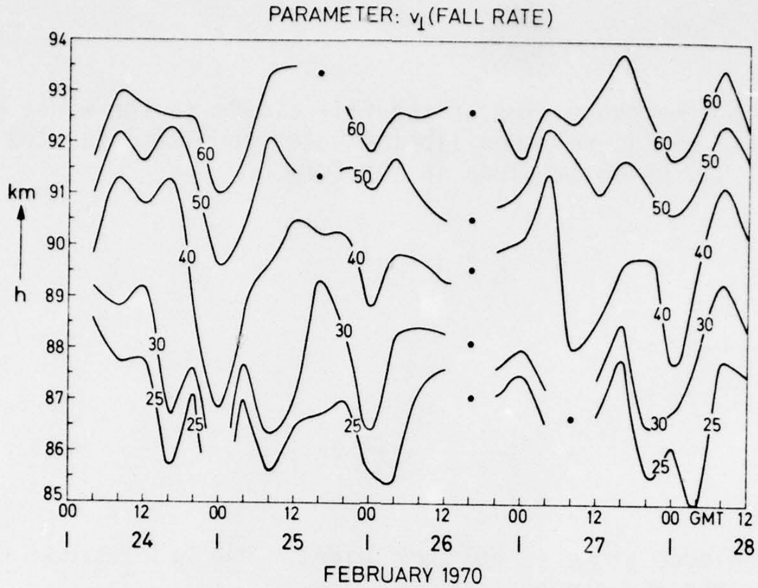

Figure 3. Variation of fall rate as a function of daytime observed on 4 consecutive days. Launches performed every fourth hour (00.00, 04.00, 08.00, 12.00, etc.) El Arenosillo, Spain.

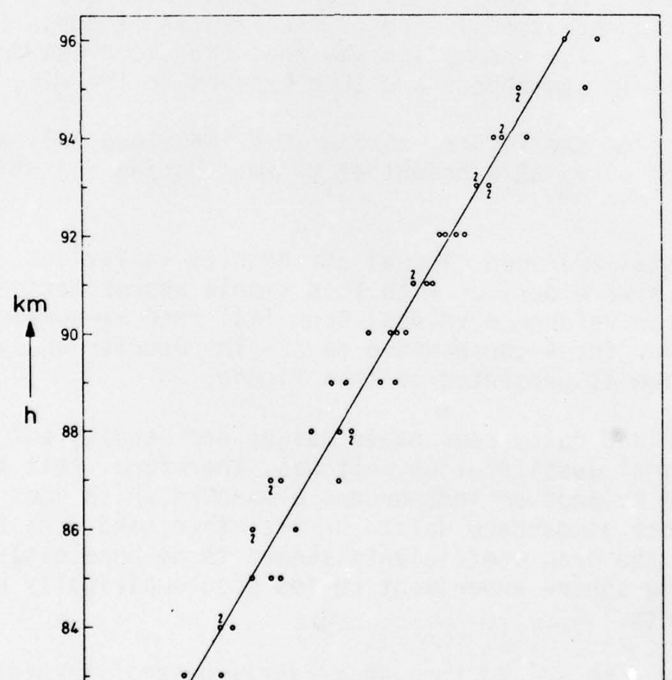

Figure 4. Variation of fall rate observed at 20.00 GMT on 4 consecutive days. Numbers in figure over or under points: number of identical values measured. El Arenosillo, Feb 70. Compare data scatter with those of fig 7.

To estimate the response time of the foil clouds to the wind, one has to know (matching of the fall equilibrium rates to CIRA data) the drag coefficient, C_D, which is given in the form

$$C_D \propto C \cdot \rho^{\gamma} v^{\theta} , \tag{5}$$

with

$$\frac{1 + \gamma}{2 + \theta} = +0.76 . \tag{6}$$

But this knowledge alone is not sufficient. One has to know also at least one of the two exponents, γ or θ.

It was assumed that θ is equal to -1, which is true for small Reynolds numbers when frictional forces dominate acceleration forces as is in the case of our falling clouds. With $\theta = -1$ in equation (5) the frictional forces as given by the right-hand side of equation (4) are proportional to v as required. This additional knowledge allowed one to estimate the response times for horizontal winds. The results of these estimates are shown in figure 5. The assumption was that the cloud was dropped vertically into a calm atmosphere and then exposed to the wind flow.

As can be seen from the figure, within 10 s the cloud follows 95 percent of the windspeed of v_0 at a height of 90 km. During this time, the cloud drops 500 m.

Figure 6 indicates averaged diurnal air density variations over El Arenosillo which were derived with this simple approximation (utilizing the CIRA data for reference values) from fall rate measurements taken every fourth hour for 4 consecutive days. The Fourier analysis of the density variation is presented in this figure.

This method yielded quite reasonable values for density but lacked some deeper theoretical justification. It was, therefore, felt that it should be supplemented by another independent procedure which does not need to rely on reference atmosphere data. On the other hand, the theoretical calculation of the drag coefficients seemed to be hopelessly complicated; even the falling sphere experiment relies upon empirically determined drag coefficients.

The problem could be solved through a fairly general theoretical assumption which made use of some peculiarities of small and lightweight dipoles which cannot be used for the treatment of the behavior of falling spheres. The movement of the foil element is governed by small Reynolds number Re < 1.

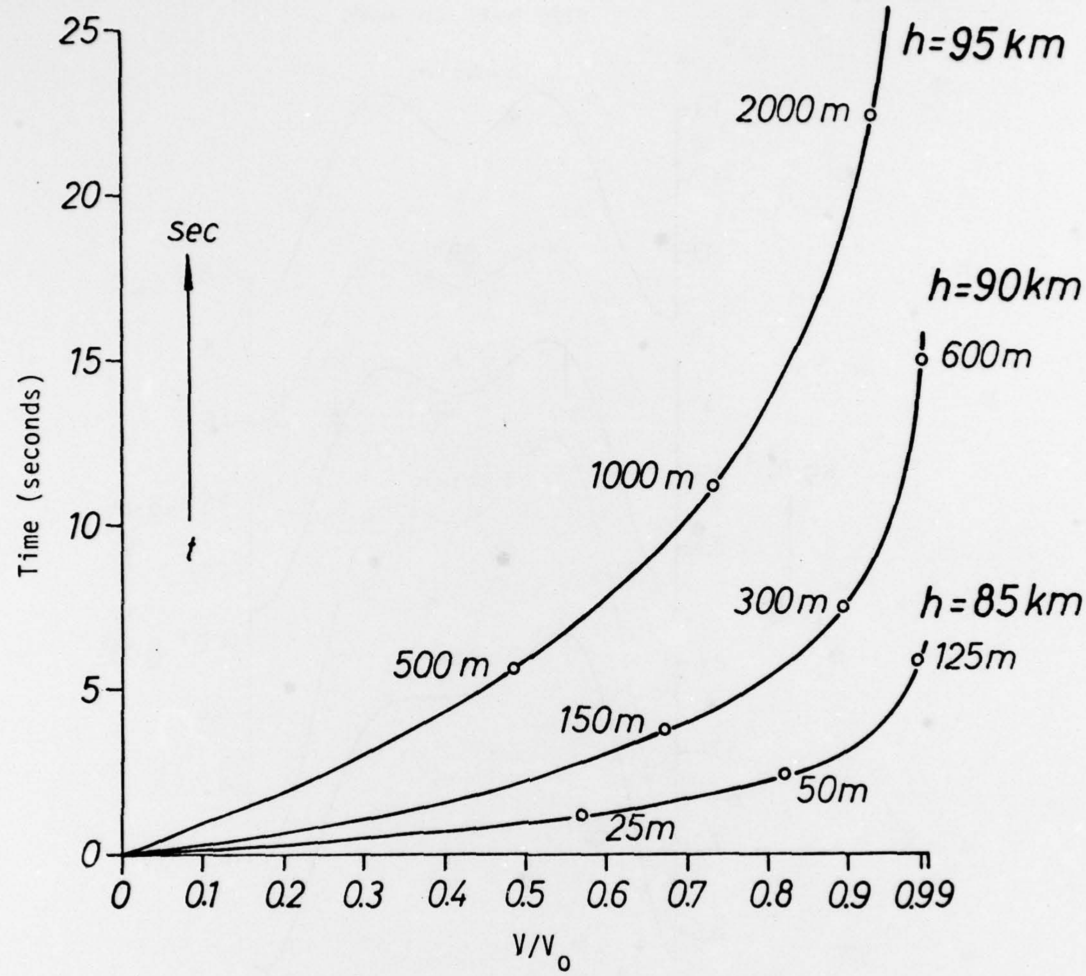

Figure 5. Response of foil cloud to wind and wind shears: falling cloud is assumed to have no horizontal velocity when exposed to wind. Time needed for the cloud to attain a certain percentage of actual windspeed present is shown for three different heights (85, 90, and 95 km), together with the heights traveled in the different height levels.

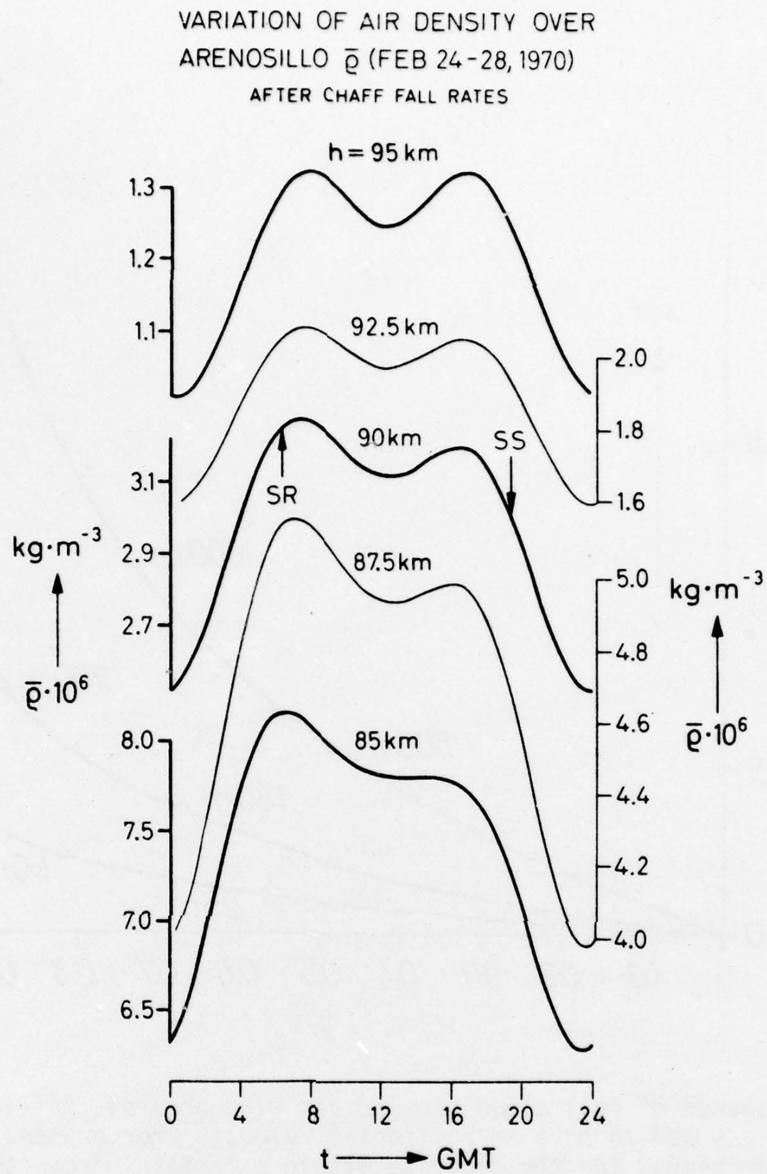

Figure 6. Fourier synthesis of diurnal variation of air density over El Arenosillo, derived from measurements on 4 consecutive days (launch every fourth hour, starting with 00.00 GMT).

Under these conditions, the drag coefficient C_D is inversely proportional to the Reynolds number for nearly all kinds of bodies; so for rectangular and circular disks, the flow is perpendicular to the surface; that is,

$$C_D = \text{const } Re^{-1} = \text{const } \frac{\eta}{v.\rho.L} , \quad (7)$$

provided that continuum flow is present. However, the measurements are not taken in the regime of continuum flow but in a regime where the mean free path of the air molecules becomes comparable with the dimensions of the dipoles. This influence of molecular flow can be reduced to the case of continuum flow with the introduction of an effective viscosity of the air:

$$\eta_{eff} \approx \frac{\eta_o}{1 + \lambda/L} . \quad (8)$$

When the classical expression for the viscosity is:

$$\eta_o = \frac{1}{3} \rho \bar{u} \cdot \lambda , \quad (9)$$

where ρ is the air density,

$$\bar{u} = \sqrt{\frac{3 kT}{\Pi \cdot m}} , \quad (10)$$

the mean thermal velocity of the air molecules, and λ their mean free path, the following expression for C_D can be used

$$C_D = \text{const } Re^{-1} = \text{const } \frac{\bar{u}}{1 + \rho \cdot L/a} \cdot v^{-1} . \quad (11)$$

L is again a characteristic length of the dipole; and

$$a = \left(4\sqrt{2} \, \Pi \, r^2 N \right)^{-1} \approx 1.2 . 10^{-7} \text{ kg/m}^2 , \quad (12)$$

the proportionality constant which reduces the inverse air density to the mean free path length ($\lambda = a/\rho$).

Finally the equilibrium descent velocity of the foil chaff dipoles for heights below 95 km is:

$$V_{\perp} = \frac{6gm}{C\bar{u}A} \; \frac{L}{a} + \frac{1}{\rho} \; , \tag{13}$$

where g is gravity acceleration, and m/Π is the mass per unit area of the chaff dipole elements. C is a constant which still has to be determined.

For the height region under consideration, air density ρ can be approximated by a simple exponential function:

$$\rho \approx \rho_0 \exp\left(-h/\bar{H}\right) . \tag{14}$$

This expression is valid for an isothermal atmosphere and replaces

$$\rho = \frac{\rho_0 T_0}{T} \exp\left(- \int_{h_0}^{h} \frac{dh}{H} \right) . \tag{15}$$

This is justified by the fact that the measurements are taken in a region where the temperature does not vary very strongly with height. For this, the isothermal case is a good approximation to reality.

In equation (13), $\bar{u}$ is replaced by the scale height $\bar{H}$. From this replacement, the expression for v is

$$V \approx \frac{\text{const}}{\sqrt{\bar{H}}} \left(\frac{L}{a} + \frac{1}{\rho_0} \exp \frac{h - h_0}{\bar{H}} \right) . \tag{16}$$

A linear relation is obtained between the descent speed v and the exponential function of the height with the scale height $\bar{H}$ as a parameter. In such a case, the procedure of "maximum likelihood" can be applied (which means in this case an optimum fitting of the measured data to theory) to calculate the scale height, $\bar{H}$, the value of const 1/a, and const/$\bar{H}$.

By this method (because 1/a is known from theory), the reference value ρ_0 (density at reference height h) and the total variation of density are determined. $\bar{H}$ is a measure of the temperature of the equivalent isothermal atmosphere.

Figure 7 shows the fall rates (with the optimum fitted mean curve) measured on 13 experiments in February 1970 over El Arenosillo.

The behavior of the very light foil elements at the high altitudes can be evaluated qualitatively. Because the movement of the foil element is governed by small Reynolds numbers, the free-fall movement of the elements is decelerated mainly by frictional forces rather than by the acceleration of large air masses. Therefore, the equilibrium descent velocity is to a very good approximation inversely proportional to the ambient viscosity (after an initial acceleration phase had been achieved after deployment which is not shown in figure 7). When the free path of the air molecules is small compared to the dimensions of the moving body, the effective viscosity is totally independent of the gas density. Therefore, the fall rate of the foils tends to vary only little with height in the lowest part of the range of measurements, while at the greater heights, the small dipoles tend to fall proportional to the mean free path of the molecules, that is, proportional to ρ^{-1}, and vary nearly exponentially with height.

The nonsystematic errors present in these procedures had been estimated by statistical analysis. Because the foil clouds are exposed at different heights to various degrees of turbulent motions, deviations of measured fall rates from those calculated are observed (figure 8). These deviations observed in a larger number of measurements can be taken together statistically and used as model calculations to determine the magnitude of errors. Such an analysis (documented in Rose and Widdel[8]) for a single measurement of pressure (determined from density and temperature) yielded an error of about 8 percent (or, more accurately, between 7 percent and 9 percent with error probability of 5 percent) for the center of a 10-km wide slab centered around 87.5 km. The error bars for air density and average temperatures were 20 and 23 percent, respectively. These values depend critically upon the quality of radar tracking. For this data set, an MPS 19 radar was used for tracking.

Figure 9 shows the variation of air density observed over El Arenosillo at local noon between November 1968 to June 1972. Compared with CIRA 65-reference atmosphere, indicated by the dashed lines, 95 percent of all air density should occur. Figure 10 shows mean temperature values determined during present campaigns.

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[8]G. Rose and H. U. Widdel, 1973, "Results of air temperature, density and pressure measurements obtained with the aid of foil cloud sensors in the height region between 80 and 95 km," Planet Space Sci, 21:1131-1140

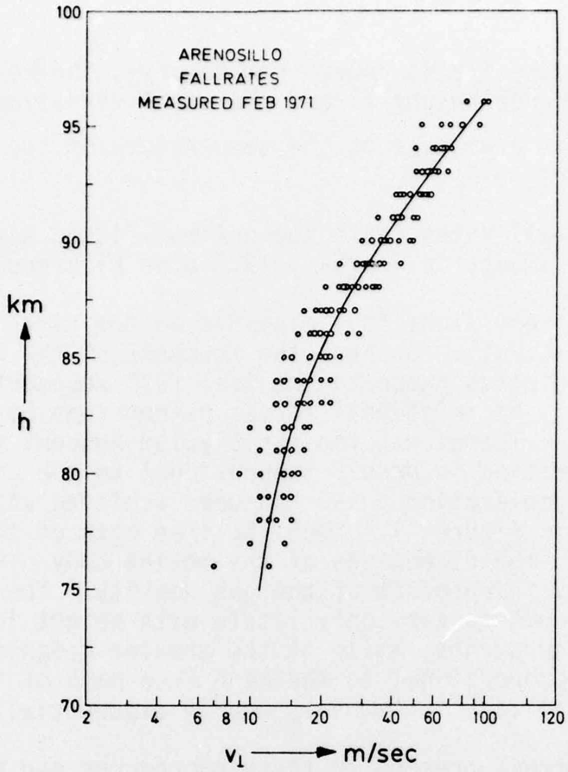

Figure 7. Compilation of measured fall rates done at noontime over El Arenosillo (Feb 71, 13 experiments).

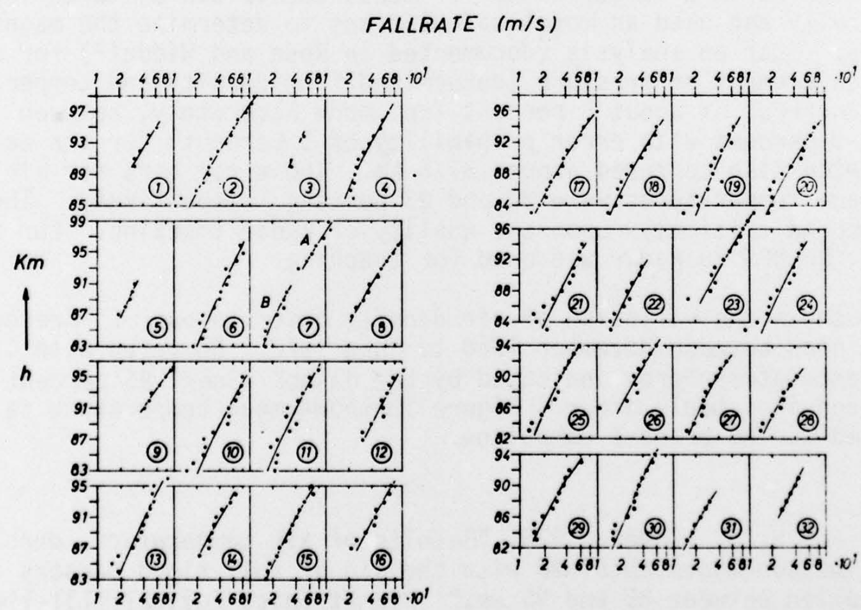

Figure 8. Variations of fall rate measurements performed over El Arenosillo, indicating turbulent motions (curve of best fit is entered into data points). The numbers indicate the chronological sequence.

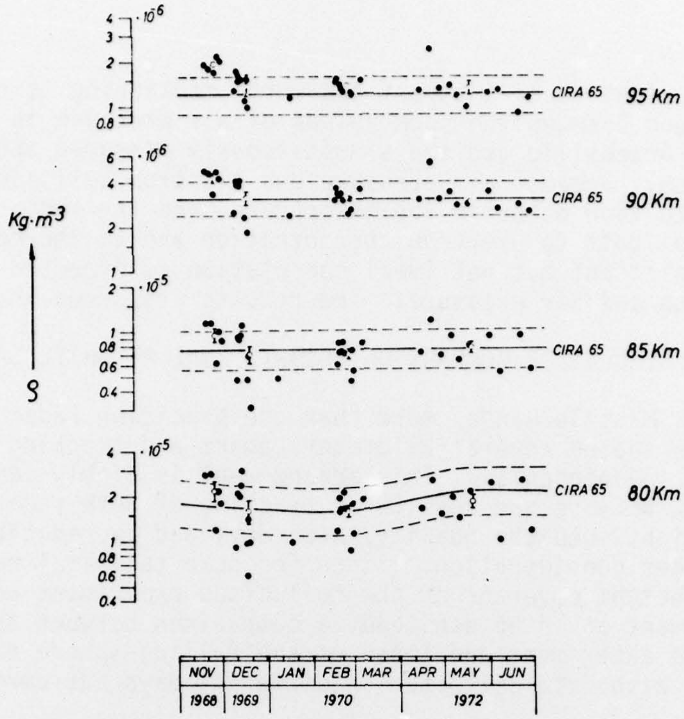

Figure 9. Seasonal variation of density derived from foil cloud measurements over El Arenosillo (noon values) compared with CIRA 65 data for different height levels. According to CIRA 65, 95 percent of all density variations should lie between the dashed lines.

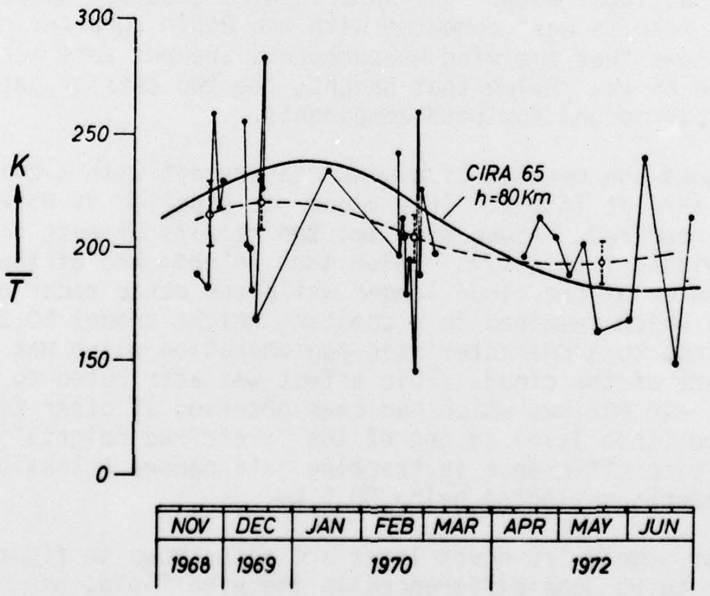

Figure 10. Comparison between mean values of temperature at noon derived from fall rate analysis of foil clouds and CIRA 65 data. Dashed curve: freehand curve laid through our foil cloud data. White points with error bars: means of foil cloud data. (Height intervals of averaging correspond to fig 8.)

A check which might be of interest and worth mentioning is the empirical connection found between the noon values of air pressure in a height of 85 km over El Arenosillo and the simultaneously measured shortwave radio wave absorption. Because air pressure and electron collision frequency are proportional to each other in the mesosphere, and the radio wave absorption is proportional both to electron concentration and to the collision frequency, a significant but not ideal correlation is expected between radio wave absorption and air pressure. The results are shown in figure 11.

THE RESULTS OF COMPARISON FLIGHTS DONE AT WHITE SANDS

At White Sands Missile Range, more than one precision radar is available. The radars are spaced several kilometers apart and tracking is done simultaneously but independently. This arrangement is highly desirable for the experiment because the results of tracking of both radars allow an immediate insight into the quality, accuracy, and reproducibility of the experiment under consideration. Since for some technical reason no simultaneous height coverage of the foil cloud experiment and falling-sphere experiment could be achieved, a comparison between the results of the foil cloud experiment and those of the falling-sphere experiment was only possible with data collected on different days but during the same month.

This procedure is reasonable, however, only for densities and temperatures. The winds may vary greatly from day to day, especially during the launch series period, and should be considered separately. Figure 12 shows the results of the wind measurements performed with falling spheres on 10 and 17 April around local noon. The spheres were tracked independently by two radars. The results were computed with the Robin computer programs. The figure shows that the wind measurements are not very accurate for heights above 85 km. Below that height, the two sets of data differ by some meters per second for both components.

Figure 13 shows the results of a wind measurement with a chaff cloud made on 22 April 1974 at 1631 Z. This cloud was expelled at 85 km, a lower apogee than required. Above 80.5 km, the results of both tracking data sets agree within 1 to 2 m/s. Below that height, one of the radars did track the center of the cloud longer while the other radar observed parts of the cloud which remained in a constant height around 80.5 km and later moved downwards to a characteristic agglomeration which was present in the upper part of the cloud. This effect was attributed to the presence of turbulent air motions which had been observed at other times in that height region (this level is one of the "preferred heights"). Either this effect or a time difference in tracking data causes a loss of accuracy in wind measurements collected below 80.5 km.

Wind data for some 2-1/2 hours later are also shown in figure 14 where there appear to be some differences in the wind field, but unfortunately the data cannot be adequately compared because of the differences in the measurement interval.

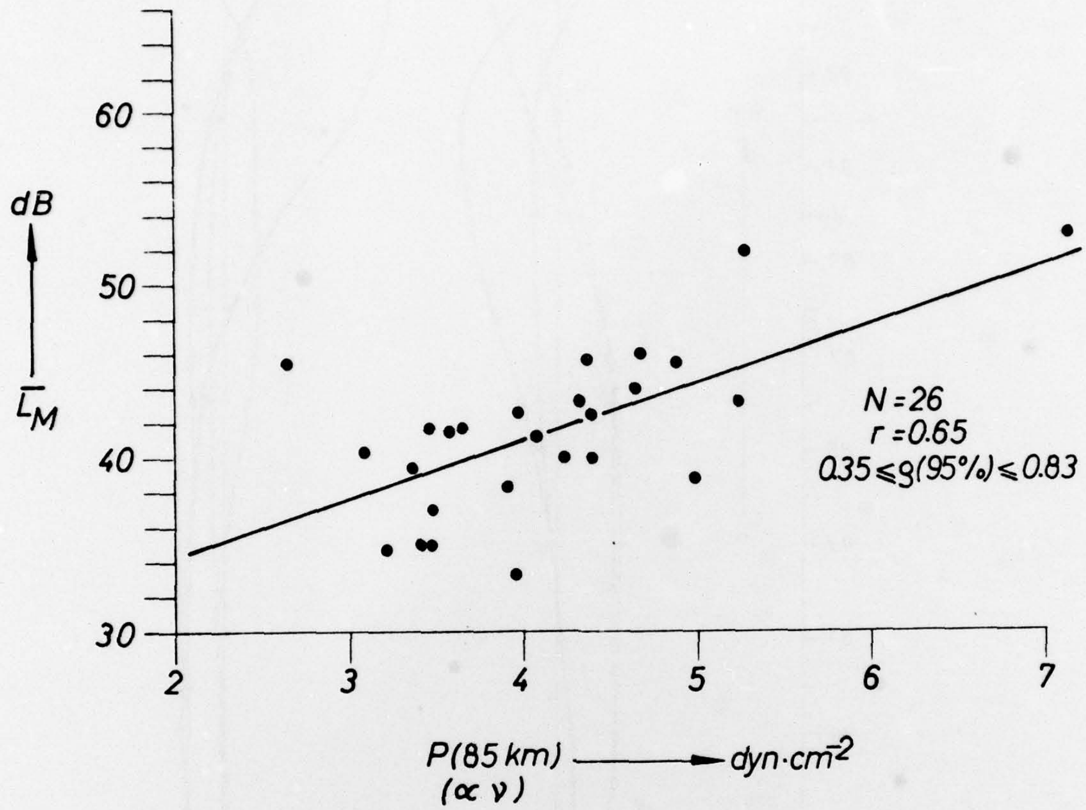

Figure 11. Correlation between noontime radio wave absorption during winter and simultaneously measured air pressure (done with foil clouds).

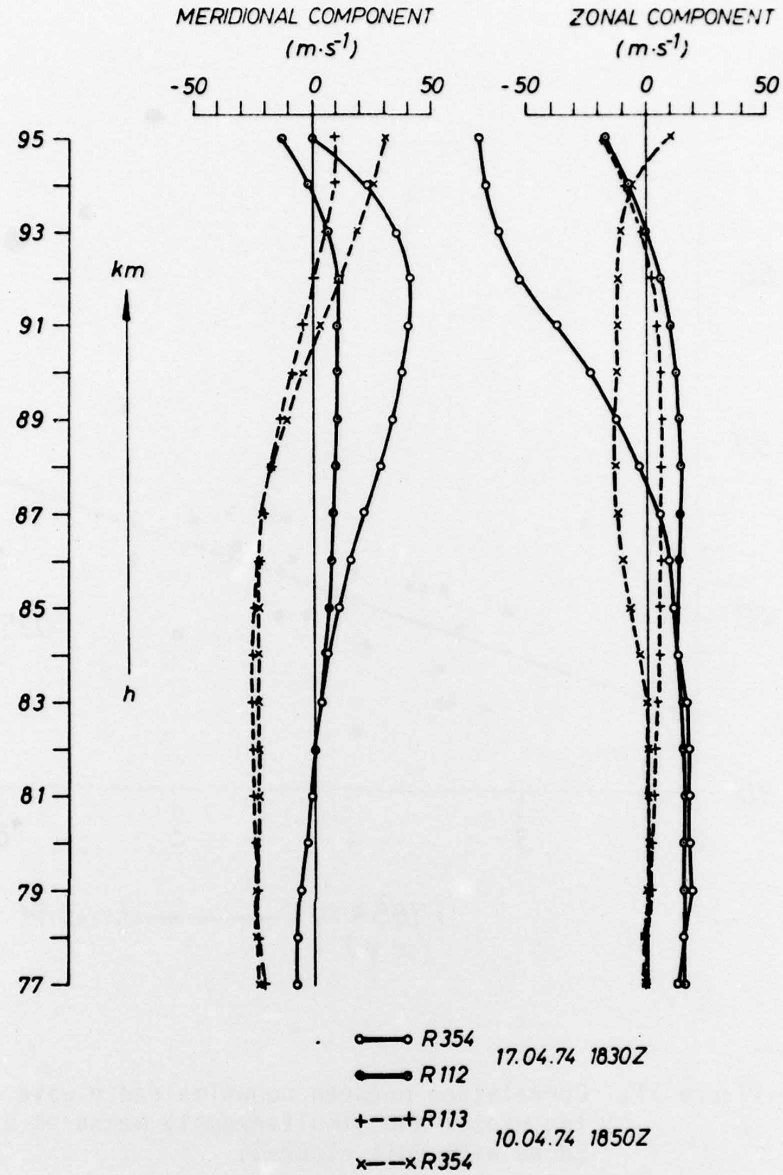

Figure 12. Wind measurements done with falling spheres over White Sands, Apr 74.

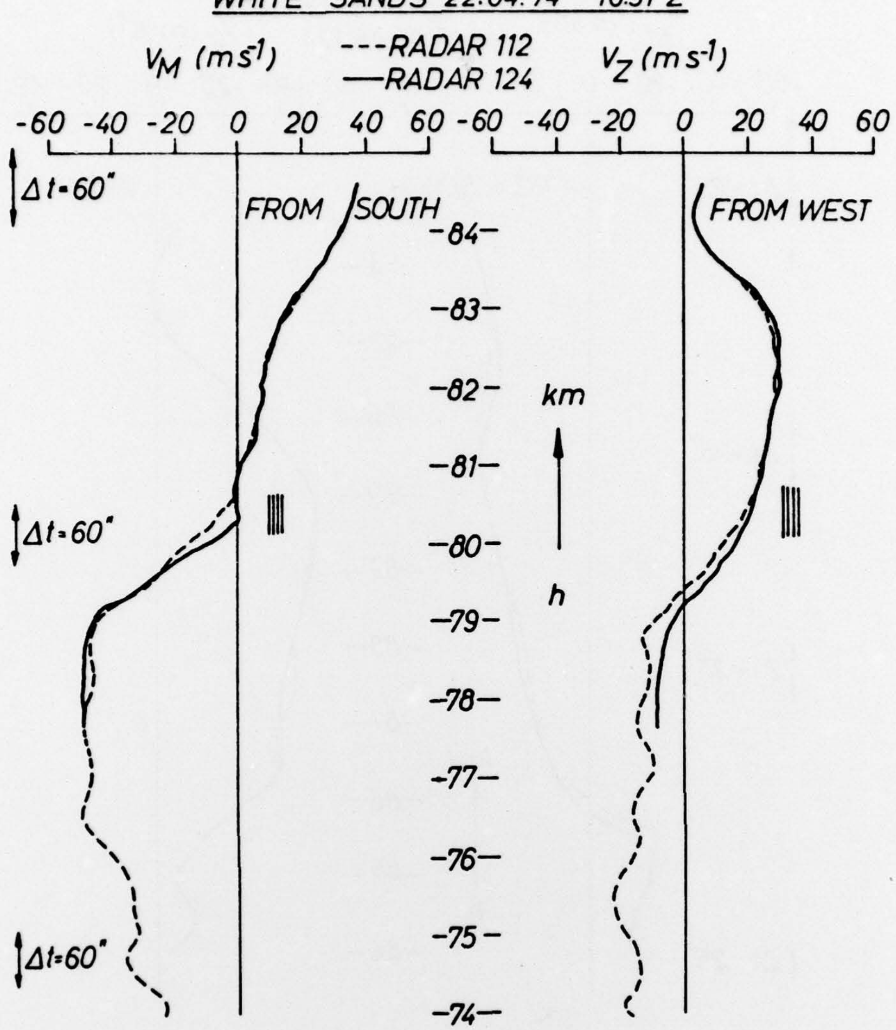

Figure 13. Wind measurement made over White Sands with foil cloud experiment (running means over 60 s. At 80.5 km probably zone of strong turbulence).

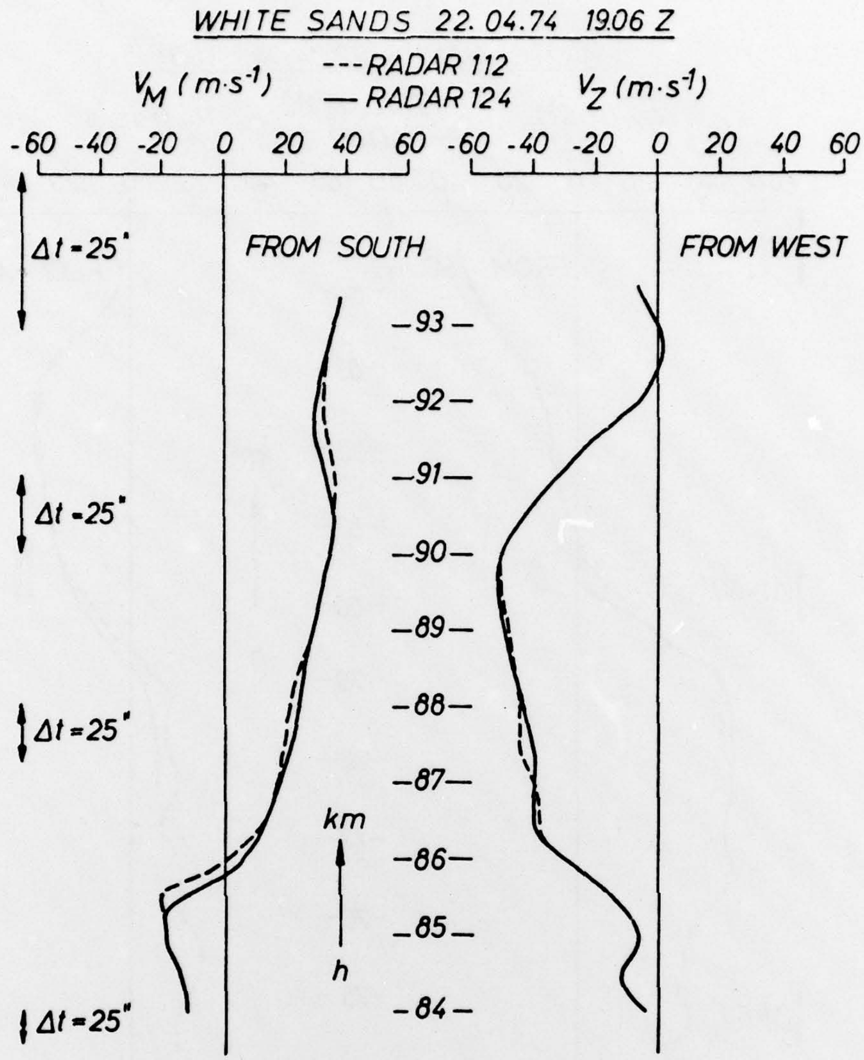

Figure 14. Wind measurement made over White Sands with foil cloud experiment (running means over 25 s tracking time). Cloud was ejected too high.

Figure 15 shows the results of two air density measurements made with falling spheres on 3 April and 10 April. They extend over the height range in which the foil cloud experiment yielded useful data. Each sphere was tracked by two radars and evaluated. As one may see from the presentation, the largest deviations of corresponding measurements are in the order of 10 to 15 percent.

Unfortunately, only the foil cloud experiment performed on 24 April at 1906 UT could be used to derive density and temperature. For the experiment on 22 April at 1631 Z, the ejection height was too low to derive data with any confidence with use of the theory outlined in the text. The dispersion of the cloud was larger than usually experienced. Because of the higher deployment altitude of the chaff cloud, the digitized radar data permitted a relatively fine evaluation in which the vertical acceleration of the cloud, $\dot{v}$, was also included (this was necessary because the cloud experienced a long quasi free-fall phase at the beginning). With appropriate methods, the tracking data for v and $\dot{v}$ obtained by the two radars were smoothed over a 4-km-wide height interval (figure 16). These data indicate the accuracy of measurement achieved under these rather unfavorable conditions. Using v and $\dot{v}$, density and temperature were calculated with the equations:

$$\rho = \frac{P}{g \cdot H} \tag{17}$$

$$T = \frac{mgh}{k} \tag{18}$$

$$\frac{1}{P} \approx \left(\frac{\dot{V}}{561 \sqrt{H}\,(1 - \dot{v}/g)} - \frac{1}{H} \right) \frac{L}{Q} \cdot \frac{1}{g} \quad (\text{kg, m, s}) \tag{19}$$

$$\frac{d}{dh} \left[\ln\left(\frac{1}{P}\right) \right] = H^{-1} \tag{20}$$

In the approximation for the inverse of air pressure in equation (19) $\dot{v}/g$ was taken into account. The value of the constant used in equation (19) has been determined from measurements made in Spain to be 561 $m^{3/2}/s$; dH/dh was considered small compared to unity and therefore neglected, but can, if necessary, be considered. A value of ± 0.1 for dH/dh produces an error for the air densities in the order of ± 4 to 5 percent as was shown in model calculations.

Figure 17 shows the results of the density measurements obtained from this experiment, determined separately from the tracking data of both radars, with the data derived from the falling spheres measurements made earlier

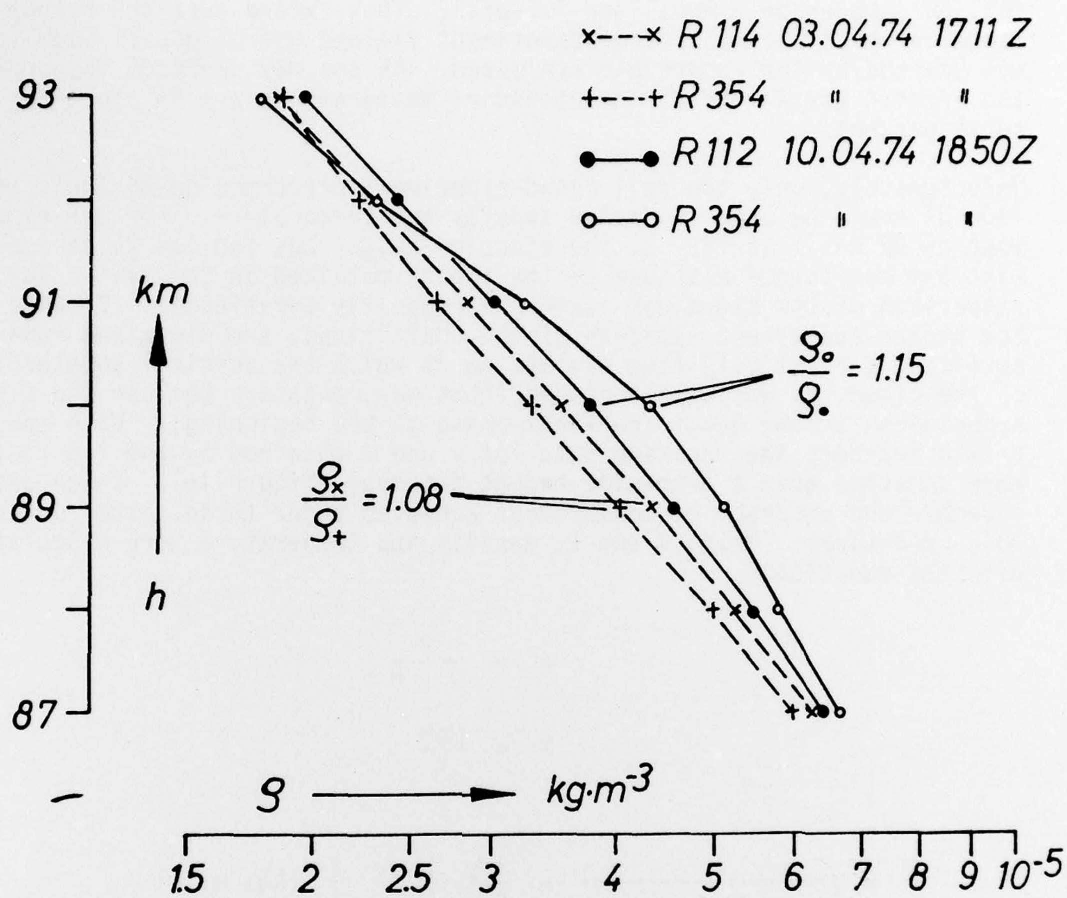

Figure 15. Results of air density measurements made with falling spheres over White Sands.

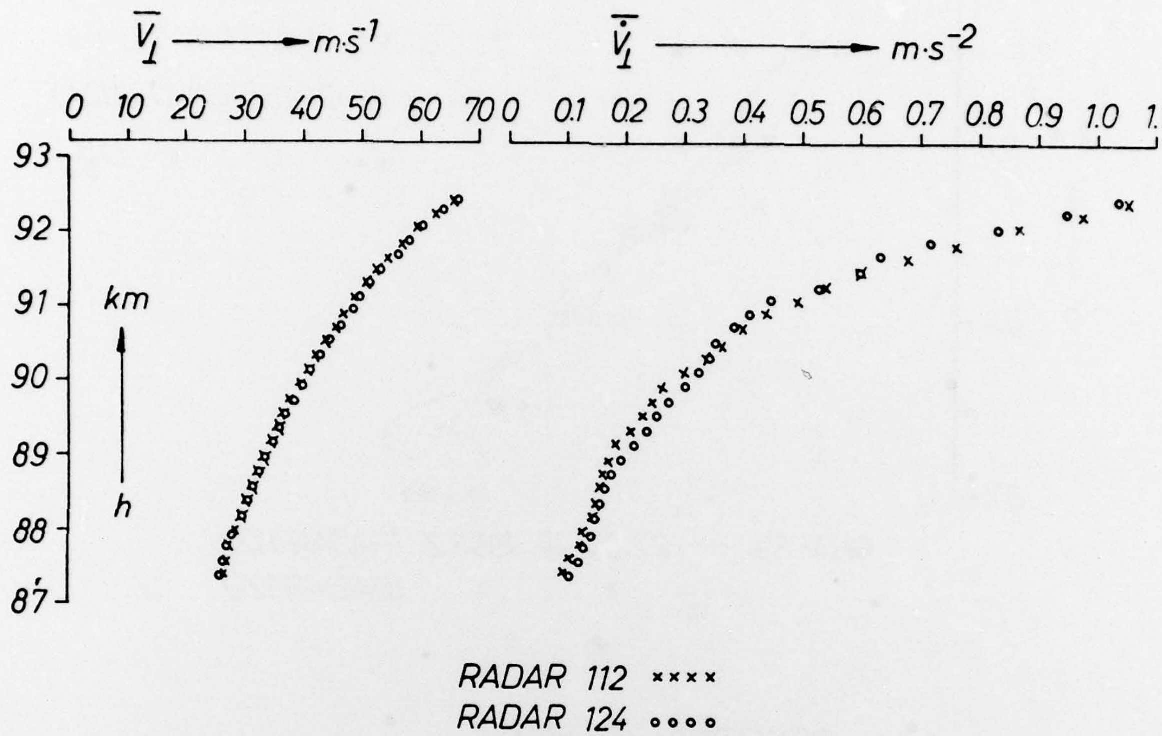

Figure 16. Descend speed and vertical deceleration of foil cloud measured with two independent radars (circles and crosses) (22 Apr 74, 19:06 Z.).

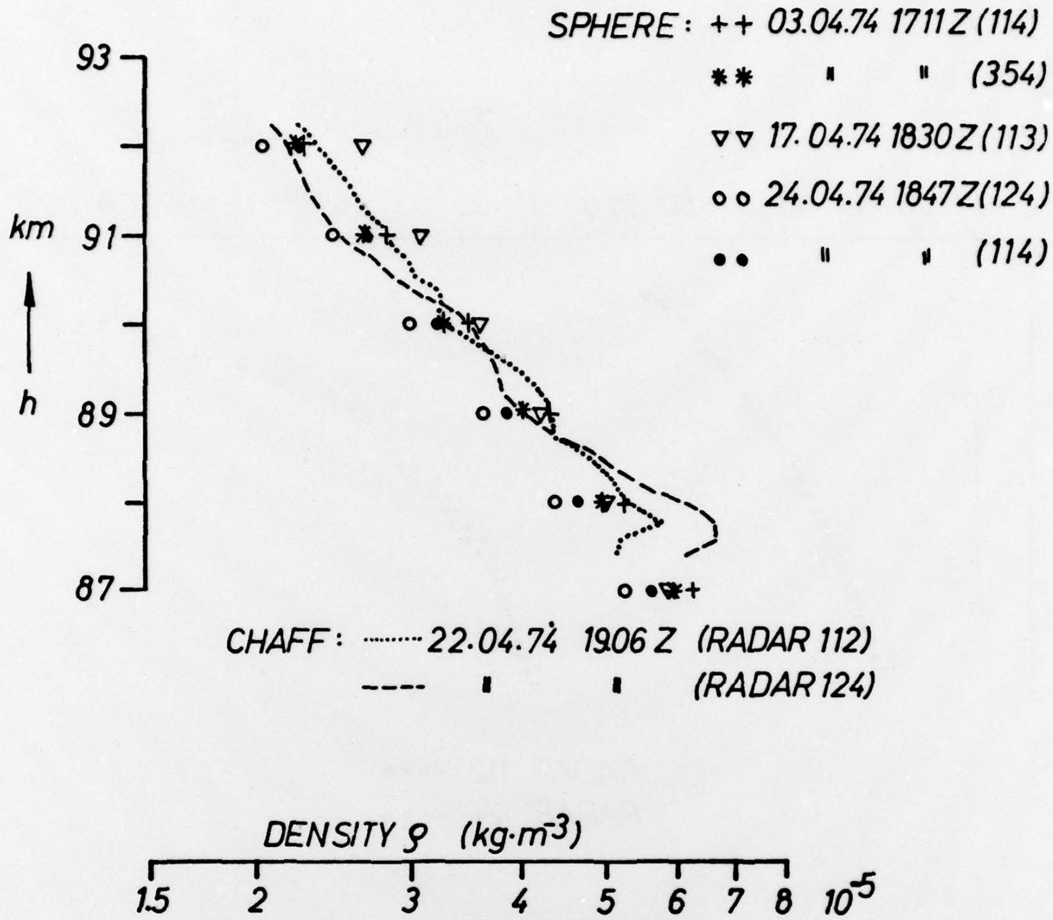

Figure 17. Comparison between density measurements done with spheres (points) and foil clouds (curves). Tracking performed simultaneously with two independent radars in all cases.

in the month. The data collected from the chaff experiment fit quite well with those derived from the falling spheres. The maximum difference between the two sets of chaff data is in the order of 15 percent, which is about the same as that obtained from the falling sphere experiments in the same height region.

Figure 18 shows a comparison of the temperature measurements derived from falling sphere data and those from the foil cloud experiments. Corresponding measurements taken with falling spheres differ from each other by 15 to 30 percent at the most. This difference gives an immediate indication of how difficult such measurements are in these heights. The foil cloud measurements differ towards lower values when compared to the means of falling sphere data. Further experiments have to be made to draw reliable conclusions on the reason for this difference.

The German contribution to this series of experiments was sponsored by the Max-Planck-Institute fur Aeronomie, the German Ministry of Defense and the European Research office, London.

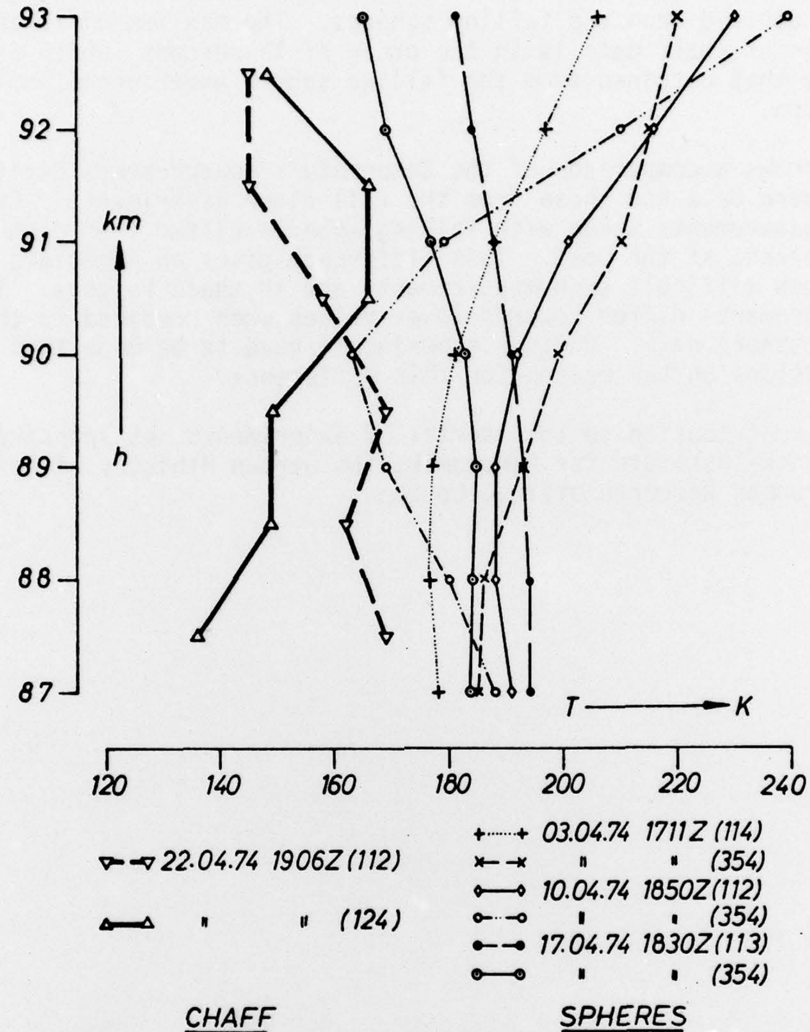

Figure 18. Comparison between temperature analysis of foil cloud and falling sphere data.

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